2022 International Symposium on Nonlinear Theory and Its Applications,
NOLTA2022, Virtual, December 12-15, 2022

Uplink Grant-Free NOMA Using Laser Chaos Decision Maker

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Abstract–Grant-free Non-Orthogonal Multiple Access (NOMA) scheme is considered a promising technique to enable massive Machine-Type Communication (mMTC) in 6G to provide massive connectivity to devices with different protocols. In a grant-free NOMA system, fast and efficient channel-power resource block selection is extremely important to guarantee communication quality for the rapidly changing communication environment, such as vehicle networks. To achieve that, we propose an uplink grant-free NOMA system using a laser chaos decision maker in this paper. In our proposed system, the channel-power resource block can be selected in real-time. Simulation results show the effectiveness of our proposed system in the probability of successful communication.

1. Introduction

The sixth generation (6G) wireless communication networks are envisioned to revolutionize customer services and applications via the Internet of Things (IoT) toward a future of fully intelligent and autonomous systems [1]. Massive machine-type communications (mMTC) are important and promising scenarios in 6G, which focuses on the uplink and aims to provide massive connectivity to devices with different protocols [2, 3]. Grant-free non-orthogonal multiple access (NOMA) scheme is a promising candidate for enabling massive connectivity and reducing signaling overhead for IoT applications in mMTC networks [4]. In grant-free NOMA systems, users can directly transmit their packets to the Base Station (BS) without requesting transmission resources. In addition, multiple users can access the same channel simultaneously by utilizing the power domain [5]. However, collisions may happen since the users select access channels and transmission power based on partial network observations without information exchange [6]. Hence, an efficient joint access channel and power selection method based on local information is necessary.

Recently, reinforcement learning (RL) has been extensively studied in wireless resource management problems due to its capability in optimization with low computational complexity [7]. There are several works on reinforcement learning-based uplink grant-free NOMA systems [7-9]. In [7], two distributed Q-learning aided uplink grant-free NOMA schemes are proposed to maximize the number of accessible devices by selecting time-frequency resources. In [8], a collaborative distributed Q-learning mechanism for MTC devices to choose their access slots is proposed. By using this mechanism, the congestion in cellular IoT networks can be significantly minimized. In [9], a NOMA-based Q-learning random access method for MTC is proposed to dynamically allocate random access slots to MTC devices to improve the network throughput. However, the related work [7] and [8] did not consider power allocation, which is very important for the performance of the NOMA system. Although ref. [9] considers the influence of transmission power on communication success rate, channel selection is not well considered.

In addition, since the communication environment of the uplink grant-free NOMA system is dynamically changing, it is necessary to select transmission parameters fast to guarantee communication performance. To achieve fast transmission parameters selection while jointly considering access channel and transmission power, we propose an uplink grant-free NOMA system using a laser chaos decision maker. Laser chaos decision maker is a bandit algorithm using chaotically oscillating time series, by which decisions can be made extremely fast [10] [11]. Laser chaos decision maker has been applied in engineering applications such as wireless communications, and its effectiveness has been indicated in several works [12-14]. In [12] and [13], laser chaos decision-maker-based user pairing schemes in downlink NOMA systems have been investigated. In addition, channel bonding schemes based on a laser chaos decision maker in the WLAN system have been presented in [14].

In this paper, we apply a laser chaos decision maker to uplink grant-free NOMA systems to achieve real-time decisions for dynamic communication systems. In our proposed system, each device selects its channel-power resource block using the laser chaos decision maker equipped with it. Besides the computational speed, our proposed system has several other advantages compared to the existing work, which can be summarized as follows. First, joint channel and power selection are considered in our proposed system compared to [7-9]. Second, resource

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blocks can be selected fast without prior information, such as path loss or fading, compared to [7] and [8].

The rest of this paper is organized as follows. Section 2 presents the system model. Section 3 introduces the laser chaos decision maker. Section 4 presents our proposed uplink grant-free NOMA system using a laser chaos decision maker. Section 5 demonstrates the performance evaluation. Section 6 concludes the paper.

2. System Model

We consider a single uplink grant-free NOMA system where there are M devices distributed in a circular cell around a BS, as shown in Fig. 1. Each device is equipped with a laser chaos decision maker to select its channel-power resource block based on the Acknowledgement (ACK)/Negative-Acknowledgement (NACK) information. Assume that the number of channels is C. Denote $\mathbb{C}=\{1,2,\cdots,c,\cdots,C\}$ as the channel set, where c denotes the c^{th} channel.

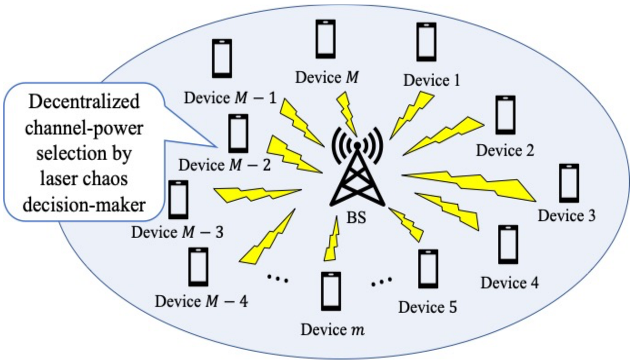

Fig. 1. System Model.

On the BS side, Successive Interference Cancelation (SIC) is performed on the overall received multiple signals starting from the strongest to the weakest. Without loss of generality, we assume that the devices using the c^{th} channel are ordered in decreasing received power from $m=1$ to $m=M_c$. Then, the Signal to Interference and Noise Ratio (SINR) for the m^{th} device in the c^{th} channel after SIC can be expressed as:

$$SINR_{m,c}=\frac{P^r_{m,c}}{\sum_{j=m+1}^{M_c}P^r_{j,c}+\bar{P}_n}, \quad (1)$$

where $P^r_{m,c}$ is the instantaneous received power from the m^{th} device in the c^{th} channel. $\bar{P}_n$ is the noise power, which can be expressed as $\bar{P}_n=FN_0B$. F is the noise figure, N_0 is the noise power spectral density, and B is the bandwidth. $P^r_{m,c}=h^2_{m,c}\bar{P}^r_{m,c}$, where $h_{m,c}$ follows Rayleigh fading, $\bar{P}^r_{m,c}$ is the average received power. We assume that the path loss follows free-space attenuation. Assume that there are P possible transmission power levels. Denote $\mathbf{P}=\{1,2,\cdots,p,\cdots,P\}$ as the possible transmission power level set. We assume that the transmission signal can be successfully decoded if the SINR at the BS is larger than the threshold from Shannon's capacity [15]:

$$SINR_{m,c}\geq 2^r-1, \quad (2)$$

where r is the spectral efficiency in bits/s/Hz. In addition, considering the SIC effectiveness, we assume that the transmission can be successfully decoded if the power difference between devices is larger than δ when multiple devices access the same channel simultaneously. As described above, the received signal can be decoded successfully when both the SINR and power difference conditions can be satisfied. This paper aims to maximize the probability of successful communication by decentralized selecting appropriate channel-power resource blocks based on the laser chaos decision maker.

3. Laser Chaos Decision Maker

In this section, we describe the principle of the laser chaos decision maker [16]. Fig. 2 shows the architecture of the laser chaos decision maker applied to the two-armed bandit problem. As shown in Fig. 2, the decisions made by the laser chaos decision-maker are based on the laser chaos time series generated by the semiconductor laser. The decision process can be briefly summarized as follows.

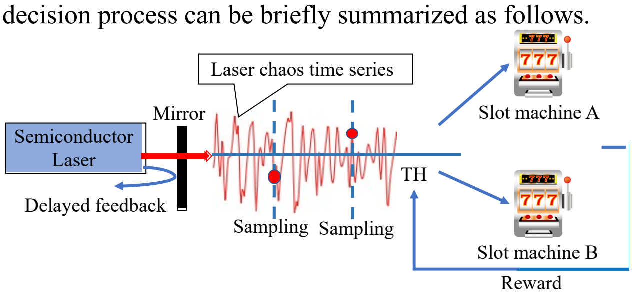

Fig. 2. Laser Chaos Decision Maker.

First, an initial value of a threshold (TH) is given. A decision is made by comparing the sampled value of the laser chaos time series with the threshold. If the sampled value exceeds the threshold, slot machine A is selected. Otherwise, slot machine B is selected. Then, the threshold is updated according to the obtained reward after playing the selected slot machine. Denote $TH(t)$ as the threshold of the laser decision maker at time t, which can be expressed as follows:

$$TH(t)=k\times\lfloor TA(t)\rfloor, \quad (3)$$

where k is the step width of the threshold adjuster value $TA(t)$. The range of the $\lfloor TA(t)\rfloor$ is set from $-N$ to N. Then, the number of the possible threshold values is $2N+1$ while the range of the $TH(t)$ is limited from $-kN$ to kN. The update of the $TA(t)$ can be expressed as follows:

$$TA(t+1)=\begin{cases}-\Delta+\alpha TA(t), & \text{if slot machine A is selected and win,}\\ \Omega+\alpha TA(t), & \text{if slot machine A is selected and fail,}\\ \Delta+\alpha TA(t), & \text{if slot machine B is selected and win,}\\ -\Omega+\alpha TA(t), & \text{if slot machine B is selected and fail,}\end{cases} \quad (4)$$

where α is a forgetting factor in reducing the influences of past experiences. Δ is a certain increment while Ω is an increment related to the success rate of the arm, which can be expressed as follows:

$$\Omega=\frac{P_0(t)+P_1(t)}{2-(P_0(t)+P_1(t))}, \quad (5)$$

where $P_0(t)$ and $P_1(t)$ are the successful probabilities of the arm with the highest and the second-highest successful probabilities at time t, respectively. $P_i(t)$ can be expressed as follows:

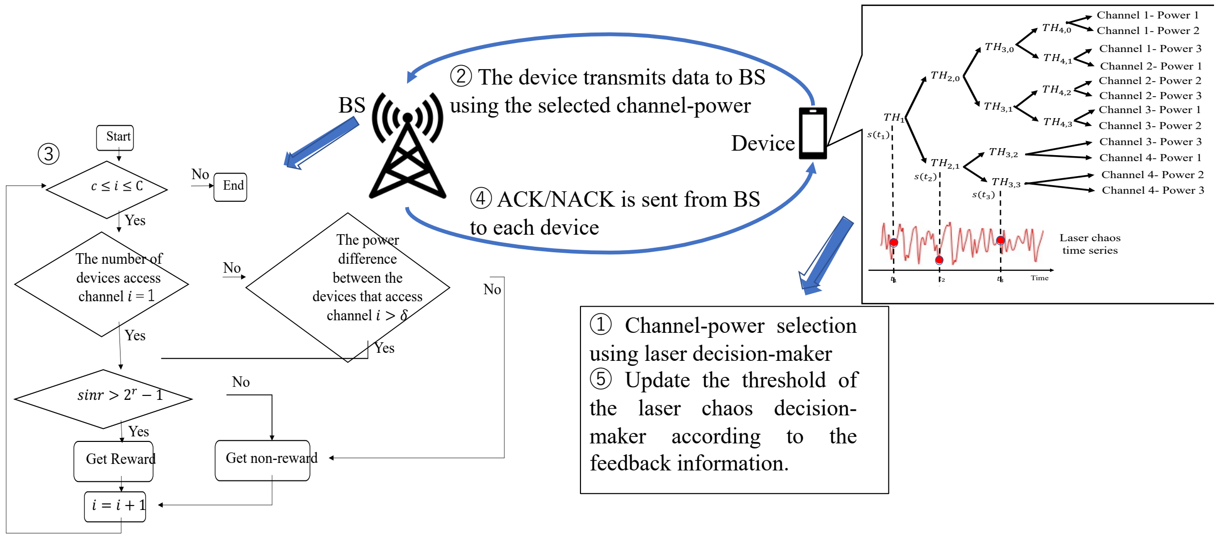

Fig. 3 Uplink grant-free NOMA system using laser chaos decision maker

$$P_i(t) = \frac{R_i(t)}{N_i(t)}, \qquad (6)$$

where $R_i(t)$ is the number of "win" times by selecting the slot machine i until time t. $N_i(t)$ is the number of times to select the slot machine i until time t. The laser chaos decision maker can be easily extended to multiple arm bandit problems by arranging pipelined thresholds [10].

4. Uplink Grant-Free NOMA Using a Laser Chaos Decision Maker

This section introduces our proposed grant-free NOMA system using a laser chaos decision maker. As shown in Fig. 3, a scalable laser chaos decision maker is loaded on the end devices, where each arm corresponds to a channel-power block. Each end device decides its channel-power resource block at each decision using the laser chaos decision maker.

The operation process of our proposed system can be summarized as follows. First, each device selects its channel-power resource block using the laser chaos decision maker. Then, the device transmits data to BS using the selected channel-power resource block. On the BS side, the BS checks the number of devices transmitted using the same channel. If only one user transmits data using the same channel, then check the SINR of the signal to confirm whether the received signal can be successfully decoded or not. If the SINR is larger than the predefined configurated threshold, the transmission is defined as successful, and a reward is obtained. If more than one user transmits data using the same channel, power differences need to be checked before checking SINR. If the difference in the power of the received signal from different users using the same channel is larger than the threshold δ, the SINR will be checked. Otherwise, the transmission is defined as failure. If the transmission is a failure, non-reward will be obtained. After checking all channels, BS sends ACK/NACK information to the users. If the transmission is successful, ACK information will be sent to the device. Otherwise, NACK information will be sent. Then, the end device updates the threshold of the laser chaos decision maker according to the feedback information.

5. Performance Evaluation

In this section, we evaluate the performance of our proposed uplink grant-free NOMA system using a laser chaos decision maker. First, we confirm the convergence of our proposed system for a varied number of devices. Then, we evaluate the probability of successful communication under the varying numbers of devices and channels. The parameter settings used in the simulation are summarized as follows. The power differs threshold δ is set as 7.78dB while the spectral efficiency r is set as 2. Two transmission power levels are considered in the simulation, i.e., 20dB and 30dB. The initial values of the $TA(1)$ and Ω are set as 0 and 1, respectively. Δ and α are set as 1.

5.1. Convergence of our proposed system

In this subsection, we confirm the convergence of our proposed system for a varied number of devices by evaluating the probability of successful communication. In the simulation, the number of channels is set to 4, while that of devices is set to 8, 12, 16, and 18, respectively. Fig. 4 shows the simulation results regarding the probability of successful communication versus the number of devices until 120 iterations. The probability of successful communication is measured based on the successful communication of all devices in the uplink grant-free NOMA system. From Fig. 5, we can see that the probability of successful communication can converge to 1 until the number of devices is 18; that is, four channels and two power levels can support the successful communication of 18 devices in our proposed system. In addition, we can see that the convergence speed decreases with the increase in the number of devices. That is, when the number of devices is larger, devices need to take more time to learn the optimal decisions.

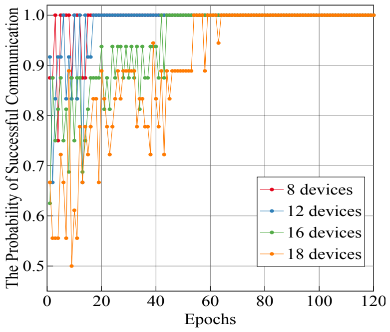

Fig. 4. The probability of successful communication versus the number of devices.

5.2. The Probability of Successful Communication versus the Numbers of Channels and Devices

In this subsection, we evaluate the probability of successful communication under the varying numbers of devices and channels. The numbers of channels/devices in the simulation are set as 4CH/8UE, 8CH/16UE, 16CH/32UE, and 32CH/64UE. Fig. 5 shows the simulation results. From Fig. 5, we can see that all the settings can converge to 1 while the coverage speed decreases with the growth of the system scale.

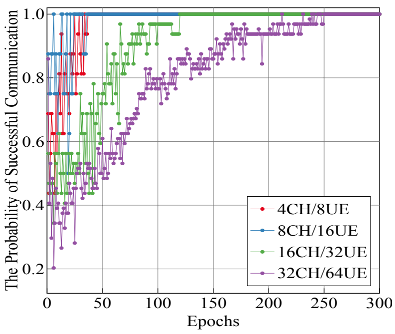

Fig. 5. The probability of successful communication versus the number of channels and devices

6. Conclusion

This paper proposes an uplink grant-free NOMA system using a laser chaos decision maker. In our proposed system, devices can quickly select their access channel and transmission power using a laser chaos decision maker. Simulation results show the effectiveness of our proposed system in the probability of successful communication. Specifically, 18 users can be supported when the numbers of the channel and the transmission power levels are set to 4 and 2, respectively. Besides, 64 devices can be supported with the probability of successful communication 1 when the number of channels increases to 32 by around 250 iterations.

Acknowledgments

This work was supported in part by CREST Project (JPMJCR17N2) funded by the Japan Science and Technology Agency and Grants-in-Aid for Transformative Research Areas (22H05197) funded by the Japan Society for the Promotion of Science.

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